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(71) Applicant: Schlumberger Limited, 277 Park Avenue, New York, N.Y. 10172 (US)

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(71) Applicant: SOCIETE DE PROSPECTION ELECTRIQUE SCHLUMBERGER, 42,rue Saint-Dominique, F-75340 Paris Cedex 07 (FR)

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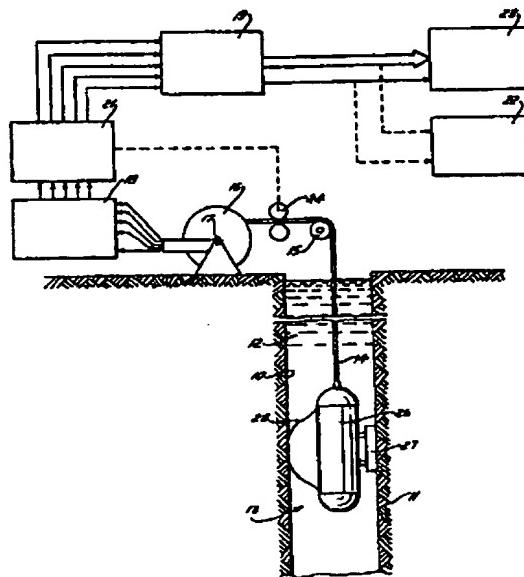
(72) Inventor: Chandler, Richard N., Beach Hill Road, Bridgewater Connecticut, 06752 (US)

(74) Representative: Chareyron, Lucien et al, Schlumberger Limited Service Brevets 42, rue Saint-Dominique, F-75340 Paris Cedex 07 (FR)

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(54) System for permeability logging by measuring streaming potential.

(57) Method and apparatus for investigating earth formations according to the present invention include positioning an opening of a fluid reservoir in contact with the surface of a earth formation to be investigated and injecting the fluid at high pressures through the opening into the formation at frequencies within a range up to 1 khz to cause quasi-static flow in the formation. Streaming potentials generated in the formation by this flow are detected by appropriate electrodes and the output of the electrodes, representative of the generated potentials, is then processed to determine a characteristic response time of these streaming potentials. Thereafter, from a knowledge of the characteristic response time of the detected streaming potentials a measurement of the permeability of the formation is derived.



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SYSTEM FOR PERMEABILITY LOGGING BY
MEASURING STREAMING POTENTIALS

BACKGROUND OF THE INVENTION

The present invention relates to methods and apparatus for investigating the permeability of earth formations traversed by a borehole, and more particularly to novel and improved methods and apparatus for determining the relative or actual 5 permeabilities of the formations by obtaining indications of a characteristic response time of streaming potentials induced by pressure pulses in the formation.

Heretofore, in some prior art practices, information 10 relating to the location and permeability of subsurface earth formations has been obtained by electrical logging methods which are based at least in part on the electrokinetic potential phenomenon that occurs when relative movement is induced between a formation and the fluid contained in the matrices of the 15 formation material. For example, in U.S. Pat. No. 2,814,017, issued Nov. 19, 1957 to Henri-Georges Doll, methods are described for investigating the permeabilities of earth formations by observing the differences in phase between periodic pressure waves passed through the formations and 20 potentials generated by the oscillatory motion of the formation fluid caused by these pressure waves. Conversely, a periodically varying electric current was suggested to be used to generate oscillatory motion of the formation fluid, which in turn generated periodic pressure waves in the formation. 25 Measurements were to be made of the phase displacement between the generating and the generated quantities and a direct indication of the relative permeability of the formation thereby obtained.

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In U.S. Patent No. 3,599,085, to A. Semmelink, entitled, "Apparatus For Well Logging By Measuring And Comparing Potentials Caused By Sonic Excitation", the application of low-frequency sonic energy to a formation surface is proposed 5 so as to create large electrokinetic, or streaming, pulses in the immediate area of the sonic generator. In accordance with the disclosure of that patent, the streaming potential pulses generate periodic movements of the formation fluid which produce detectable transient electrokinetic potentials of the 10 same frequency as the applied sonic energy and having magnitudes at any given location directly proportional to the velocity of the fluid motion at that location and inversely proportional to the square of the distance from the locus of the streaming potential pulse. Since the fluid velocity was 15 found to fall off from its initial value with increasing length of travel through the formation at a rate dependent in part upon the permeability of the formation rock, it was suggested that the magnitude of the electrokinetic potential at any given distance from the streaming pulse provided an indication of 20 formation permeability.

Although these above-mentioned methods yield useful data relating to the borehole logging of subsurface formations it is desirable to obtain permeability information through yet other 25 methods which are believed to yield more useful results. More particularly, as provided by the present invention, quasi-static flow is induced in the formation by appropriate pressure pulse excitation and a measurement of the characteristic response time of streaming potentials generated in the formation by such flow 30 is employed to derive more accurate information relating to formation permeability.

SUMMARY OF THE INVENTION

It is a general object of the present invention to provide an improved method and apparatus for determining the actual or relative permeability of subsurface earth formations.

5 The foregoing and other objects are attained, in accordance with one aspect of the invention, by comprising a method for investigating the permeability of earth formations traversed by a borehole comprising the steps of: positioning a source of periodic mechanical excitation in contact with the surface of
10 the borehole within a formation to be investigated, actuating the source to periodically excite the formation at the area of contact between the formation and the excitation source so as to cause a quasi-static fluid flow condition and accompanying periodic electrokinetic potentials to be produced in the
15 formations; simultaneously with excitation of the formation measuring the magnitude of the electrokinetic potentials excited in the formation; and determining a characteristic response time for the electrokinetic potentials excited in the formation, which response time is related to the permeability
20 of the formation.

Another aspect of the invention includes apparatus for investigating the permeability of earth formations traversed by a borehole comprising a source of periodic mechanical excitation, means for positioning the excitation source in contact with the borehole wall adjacent a formation to be investigated when said apparatus is in a borehole, means for actuating the source so that when the source is adjacent a formation it is effective to periodically excite the formation
25 so as to cause a quasi-static flow condition and accompanying periodic electrokinetic potentials to be produced in the formation; and means within said positioning means for measuring electrokinetic potentials.
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BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings:

FIG. 1 is a schematic diagram of suitable apparatus for investigating the permeability of earth formations 5 traversed by a borehole in accordance with the present invention;

FIG. 2 is a schematic diagram of certain details of the pad portion of the apparatus of FIG. 1, showing the 10 relative positions, in accordance with one embodiment of the present invention, of fluid reservoirs and electrodes;

FIG. 3 is a schematic diagram of certain details of the pad portion of the apparatus of FIG. 1, in accordance with 15 another embodiment of the present invention;

FIGS. 4(a) through 4(c) respectively are graphs of typical streaming potential pulses detected by the respective embodiments of the apparatus of Figs. 2 and 3; and

20

FIG. 4(d) is a graph of an idealized fluid pressure pulse generated by the apparatus of FIG. 1.

DESCRIPTION OF A REPRESENTATIVE EMBODIMENT

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Referring to FIG. 1, a representative apparatus for investigating the permeability of subsurface earth formations in accordance with the present invention is shown disposed in an uncased borehole 10 traversing a subsurface earth 30 formation 11 and containing a borehole fluid 12. Mechanical and electrical control of the downhole tool 13 may be accomplished with a multiconductor cable 14 which passes from

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the downhole tool 13 through the borehole to a sheave wheel 15 at the surface and then to a suitable drum and winch mechanism 16. Electrical connections between various conductors of the multiconductor cable and various electrical circuits at the surface of the earth are accomplished by means of a suitable multi-element slip-ring and brush contact assembly 17. In this manner, the signals which originate from the downhole investigating tool are supplied to a control panel 18 which in turn supplies signals to a processor 19 and a recorder 21. A suitable signal generator (not shown) supplies current to the downhole tool and to signal processing circuits forming part of processor 19, located at the surface.

15 Signals obtained from the downhole device may be recorded graphically by a plotter 22 and displayed on a CRT 23. In addition, the signals may be processed to obtain discrete samples which may then be recorded on digital tape. A suitable digital tape recorder is described in U. S. Patent 20 No. 3,648,278 issued to G. K. Miller, et al on March 7, 1972. The signals may be sampled by driving sampling devices, such as those described in the above-mentioned Miller, et al patent, by the cable motion as measured at the surface. For example, a cable length measuring wheel 24 may 25 be used in controlling the signal processing, sampling and recording functions as indicated by signal line 25. Therefore, each sample of a measured signal can correspond to one increment in depth and displacements determined between such sample signals would be indicative of depth 30 displacements.

The measured signals or samples thereof may also be transmitted directly to a computer located at the well site. Alternatively, the signals may be transmitted via a

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transmission system to a computer at a remote location. One transmission system which may be used is described in U.S. Patent 3,599,156 issued to G. K. Miller, et al on August 10, 1971.

- 5 The recorded or transmitted signals may be processed as digital measurements by general purpose digital computing apparatus properly programmed in a manner to perform the processes described herein or by special purpose computing apparatus composed of modules arranged to accomplish the
10 described steps to accomplish the same process. The signals may also be processed directly at the well site, using conventional digital computing apparatus forming part of the processor 19 when properly programmed and interfaced to signal conversion means (not shown). One such computing apparatus
15 is the Model PDP-11/45 obtainable from Digital Equipment Corporation. Suppliers of such equipment may also supply signal conditioning circuits and signal conversion means suitable for conditioning and converting analog signals to digital samples for subsequent digital storage and
20 processing. Further, such computing apparatus ordinarily include a memory for storing data and information such as parameters, coefficients and controls used and generated by the processing steps.
- 25 The well tool 13 comprises an elongated housing 26 having a pad device 27 for engaging the surface of the formation 11 and means, such as the diametrically disposed, wall-engaging bow spring 28, for resiliently urging the housing 22 and the pad device 27 toward the opposite borehole
30 wall to hold the pad device 27 in firm engagement with the surface of the formation.

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The pad device 27 preferably conforms generally to the contour of the borehole wall and is supported on the housing 22 by extensible members so as to be selectively moveable between an outboard, wall-engaging position and an inboard, 5 retracted position. In the illustrative embodiment shown, the logging device is maintained at the inboard position during movement of the tool 13 in the borehole and is caused to be extended from the housing into engagement with a formation to be tested, for example, by activation of a 10 hydraulic system from the ground surface.

With reference to FIGS. 2 and 3, the pad device 27 includes pressure inducing means 29 comprising fluid reservoirs with restricted openings. When the pad device 27, 15 only portions of which are shown for purposes of clarity, is in the wall-engaging position the openings are brought into contact with the adjacent surfaces of the formation. The means 29 may be energized by a suitable source of electrical energy (not shown) which may be controlled from the surface. 20 Electrokinetic potentials resulting from the fluid flow created in the formation by the applied pressure pulses are detected by a system of electrodes mounted on the pad device 27 and connected through appropriate conductors in the cable 14 to the surface apparatus.

25

In operation, the well tool 13, is positioned opposite a formation to be investigated, the pad device 27 is extended into engagement with the formation surface and the pressure inducing means 29 is activated to excite the 30 formation with pressure pulses the frequency of which is low and typically within a range of up to 1 khz. Thereafter, and while the formation is being excited, the magnitudes of the resultant electrokinetic potentials are detected by the electrodes so that reliable indications of the several

potentials are obtained. The measurements may be made continuously over a 4 to 5-cycle period of excitation and then averaged if desired.

5 With particular reference to Fig. 2, the pressure pulse generating means 29, in accordance with one embodiment of the invention, comprises two fluid reservoirs 30 and 32, having respective spaced apart openings 34, 36 which communicate with the environment outside the pad device 27.
10 The openings are arranged so as to be flush with the borehole wall, i.e., the formation, when the logging device is in the wall-engaging position as discussed above. The reservoirs 30 and 32 respectively comprise bellows arrangements 38 and 40 for effecting the ejection of a fluid, contained in the
15 reservoirs, through the respective openings 34 and 36. In this embodiment the bellows are shown to be driven by a single, common motor 42 which, upon application of suitable driving current to the motor, drives the bellows 38 and 40 in opposition producing a differential pressure of alternating
20 polarity in the adjacent formation. Ring electrodes 44 and 46 are provided around the respective openings 34 and 36. These electrodes are insulated the one from the other and are respectively coupled to an operational amplifier 48 whose output E_s is the magnitude of the streaming potential
25 difference between the electrodes.

While water is an excellent example of a fluid which may be employed in the reservoirs other fluids, such as aqueous borehole fluids, are also suitable. The volume of the
30 reservoirs, relative to the amount of fluid necessary to effect production of the pressure pulses, is large enough so that the system may be operated for a considerable amount of time before the fluids are depleted or contaminated to a degree which necessitates replenishing the reservoirs. In

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any case, if borehole fluid is not suitable, additional supplies of fluid may be stored in the tool to effect automatic resupply of respective reservoirs.

5

To better understand the operation of the apparatus of FIG. 2, some of the theoretical considerations governing its operations are discussed below.

10. The electrokinetic variables streaming potential (E_s) and differential pressure (ΔP) are simply related by

$$\frac{E_s(t)}{\Delta P(t)} = \frac{\epsilon \zeta}{4\pi\mu\sigma} \quad (1)$$

- 15 provided that: (a) the flow is laminar, (b) all pore (capillary) radii are much smaller than the electro-chemical double layer thickness, and (c) surface conductance does not dominate that of the bulk fluid. Here ϵ is the dielectric constant, σ is the conductivity, μ is the viscosity of the
20 fluid, and ζ is the zeta potential characterizing the solid-liquid surface. Equation (1) has been derived in the literature for porous plugs and has been shown to be a direct consequence of Onsager's principle of irreversible phenomena. Reference may be had to the following for
25 background information: H. R. Kruyt, Colloid Science I, Elsevier Publishing, 1952; P. Sennett, J. P. Olivier, Colloidal Dispensions, Electrokinetic Effects, and the Concept of the Zeta Potential, Chemistry and Physics of Interfaces (D.E. Gushee, Editor), American Chemical Society
30 Publications, 1965; and P. Mazur, J. Th. G. Overbeek, Rec. trav. chim. 70, 1951. Thus it may be established that the temporal behavior of the streaming potential follows that of differential pressure.

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Consider a spherical fluid injection source of radius "a" inbedded in an infinite homogeneous porous media. If fluid is injected into the media from a flexible reservoir of cross-section A, length ℓ and Young's Modulus Y, then the 5 volume flow rate everywhere is:

$$Q = A\Delta\ell \quad (2)$$

The velocity is:

$$10 \quad \bar{q}(r,t) = \frac{Q(t)}{4\pi r^2} \hat{r} \quad (3)$$

Darcy's law demands:

$$\bar{q}(r,t) = \frac{k}{\mu} \overline{\text{grad}} p(r,t) \quad (4)$$

where k is the permeability of the media; and the

15

boundary condition on pressure p are

$$p(r=\infty, t) = 0 \quad (5)$$

$$20 \quad p(r=a, t) = P_0(t) - y \frac{\Delta\ell}{\ell} \quad (6)$$

when $P_0(t)$ is an applied force on the reservoir. The solution to this set of equations is, at a distance R from the injection port,

$$25 \quad E_s(R, t) = -\frac{\epsilon\zeta}{4\pi\mu\sigma} P_0(1-a/R) \exp(-t/T_{\text{bellows}}) \quad (7)$$

where the characteristic response time depends simply on flow permeability:

30

$$T_{\text{bellows}} = \frac{A\ell}{4\pi a Y} \frac{\mu}{k} \quad (8)$$

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Because A, l, a, and y are known constants of the reservoir and the viscosity of water is known, permeability may be directly calculated from $T_{bellows}$ as explained below.

5 Deviations from spherical geometry affects this result only through a geometric factor. The simple relationship between response time and permeability is unchanged.

10 Turning again to FIG. 2, regarding measurements at one borehole depth, the output potential E_s is the difference in magnitude between the streaming potentials measured at the ring electrode 46 and that of the streaming potentials measured at the ring electrode 44. E_s is then determined to obtain indications of the rate of fall-off in fluid pressure
15 in the formation. $T_{bellows}$ can be derived from the slope of the trailing end of this rate by linear regression. Once $T_{bellows}$ is derived equation (8) may then be employed to provide a measurement of formation permeability.

20 With reference now to FIG. 3, another embodiment for the pad device 27 of the apparatus of the present invention is shown. This embodiment comprises a single fluid reservoir 48 and bellows arrangement for ejecting the fluid that is in the reservoir in a manner effecting the production of
25 quasi-static flow in the formations adjoining the opening 52 when the pad is in a wall engaging position in a borehole as previously described. A ring electrode 54 surrounds the opening 52 and additional, spaced apart electrodes 56, 57, 58 and 59 are provided on the pad device 27. All of the
30 electrodes are electrically insulated the one from the other and may be arranged along the pad device 27 so as to be co-linear. Pairs of electrodes are coupled to respective operational amplifiers to derive differential potential measurements.

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In pursuit of that object, electrode 56 is coupled to operational amplifiers 60 and 61 which respectively receive the outputs of electrodes 58 and 54 and electrode 57 is coupled to operational amplifiers 62 and 63 which 5 respectively receive the outputs of electrodes 59 and 54. Another pair of operational amplifiers 64 and 66 respectively receive the outputs of operational amplifiers 60 and 62 and the outputs of operational amplifiers 61 and 63. For purposes of simplification the output of operational 10 amplifier 64 is designated V23 and is illustrated in FIG 4(c) and that of operational amplifier 66 is designated V13 and is illustrated in FIG. 4(b).

The apparatus of FIG. 3, provides certain advantages 15 over that illustrated in FIG. 2. In addition to the simplified pressure pulse generating arrangement, major advantage is realized when the assumption of the form of the pressure pulse, which is idealized in FIG. 4(d), is replaced by an actual measurement of that waveform obtained by taking 20 differential potential measurements between electrodes 56, 54 and 57 to obtain the measurement V13 illustrated in FIG. 4(b). Differential potential measurements between electrodes 56, 58, 57 and 59, as described above, provide the measurement V23, illustrated in FIG 4(c), which measurement 25 is representative of the streaming potentials generated in the formations near the location where the pressure pulses are applied both for a short rise time T_{fluid} and the long decay time $T_{bellows}$ as further explained below.

30 The essential feature of the technique as discussed with reference to the embodiment of FIG. 2, is still valid for the embodiment of FIG. 3, therefore, the conclusion that the flow permeability and characteristic response time of the

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streaming potentials are simply related still applies. It will be illustrated below that for both the short rise time T_{fluid} and the long decay time $T_{bellows}$ the following relationship holds:

5

$$T_{fluid} \approx T_{bellows} \approx 1/k$$

To better understand the operation of the FIG. 3 embodiment, some of the theoretical considerations governing 10 its operations are discussed below where it is illustrated that a permeability measurement can be derived from the characteristic response time of streaming potentials for the short rise time T_{fluid} .

15 The constitutive relations for a water-saturated soil can be derived by generalizing Hooke's Law and including the effect of pore pressure on the principle solid strains only. The following equations were derived for the solid skeleton 20 by M. A. Biot. Reference may be had to an article published in the Journal of Applied Physics, Volume 12, pages 155-164 (1941) and authored by Biot. For incompressible fluid the constitution relations are:

25

$$2G \epsilon_{ij} = \sigma_{ij} - \frac{\nu}{1+\nu} \alpha_{kk} \delta_{ij} + \frac{2G}{3H} p \delta_{ij} \quad (10)$$

where

G = Shear Modulus.

30

E = Young's Modulus.

ν = Poisson's Ratio.

p = Pore Pressure.

H = Biot's experimental constant measuring aggregate dilation for a change in pore pressure.

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σ_{ij} = Total Stress Tensor.
 ϵ_{ij} = Solid Strain Tensor.

and all material parameters represent the aggregate under
 5 drained (constant pore pressure) conditions; and

K = Bulk Modulus of Solid Frame:

$$10 \quad K = \frac{2G(1+\nu)}{3(1-2\nu)} \quad (11)$$

where the Einstein convention of repeated indices implying summation has been adopted. Thus σ_{kk} is the hydrostatic stress:

$$15 \quad (\sigma_{kk} = \sigma_{11} + \sigma_{22} + \sigma_{33}).$$

For the fluid, the constitutive relation is

$$20 \quad \Delta\phi = \frac{1}{3H} \sigma_{kk} + \frac{P}{R} \quad (12)$$

where R is another experimental constant and ϕ is the porosity
 Geertsma and Smit, Geophysics, Vol. XXVI, No. 2 April, 1961,
 make the identification:

$$25 \quad \begin{aligned} \frac{1}{H} &= \frac{1}{K} \left[\frac{1-K/K_s}{1+K/K_s} \right] \\ \frac{1}{R} &= \frac{1}{K} \left[\frac{1-K}{K_s} (1+\phi) \right] \end{aligned}$$

where K_s is the bulk modulus of the solid grains. The
 30 constitutive relations then become:

$$\begin{aligned} 2G\epsilon_{ij} &= \sigma_{ij} - \frac{\nu}{1+\nu} \sigma_{kk} + \frac{(1-2\nu)}{1+\nu} (1-K/K_s) P \delta_{ij} \\ \Delta\phi &= \frac{1}{3K} \left(1-K/K_s \right) \sigma_{kk} + \frac{P}{K} \left(1 - \frac{K(1+\phi)}{K_s} \right) \end{aligned} \quad (13)$$

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The linearized change in fluid mass within a volume element of aggregate is:

$$5 \quad \Delta m_f = \phi_0 \Delta \rho + \rho_0 \Delta \phi \quad (14)$$

where ϕ_0 , ρ_0 are the unstressed reference values of the porosity and fluid density, respectively. The equation of state for the fluid is:

$$C_p^2 = \frac{K_f}{P_o} = \frac{P}{P-P_o} \quad (15)$$

where K_f = Bulk Modulus of the fluid.

Mass conservation within a unit volume element requires:

$$q_{i,i} + m_{,t} = 0 \quad (16)$$

Pore fluid diffusion in a homogeneous media is governed by the Darcy equation:

$$q_i = - \frac{\rho_0 k}{\mu} p'_{,i} \quad (17)$$

3a. Finally, the equation of momentum conservation is,
for no body forces

$$\sigma_{ij,j} = 0 \quad (18)$$

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Combining these equations, one obtains, for the cases of time-independent boundary conditions (including Heaviside functions) or infinite spatial extent (i.e., single dimensional flow), a homogeneous diffusion equation in pore pressure alone:

$$C_D P_{,zz} - P_{,t} = 0$$

where C_D = fluid diffusivity = $\frac{k K_{eff}}{\mu \phi}$ (19)

and K_{eff} = Effective Modulus
 $= K_f \left[1 + \frac{K_f}{\phi(K+G)} \right] \left\{ 1 + \frac{1}{K_s} \left[\frac{4}{3} G (1-K/K_s) - K - \phi(K+\frac{4}{3}G) \right] \right\}^{-1}$

the solutions of which are well covered in the literature.

Reference may be had to a 1959 Clarendon Press publication by H. S. Carslaw and J. C. Jaeger entitled "Conduction of Heat in Solids" for such solutions. The fluid modulus K_f and viscosity are known constants, as is the modulus of the rock grains K_s . Porosity and the moduli K_f and G are obtainable from acoustic logs and to a very good approximation, may be obtained from the acoustic compressional velocity alone.

One may then wish to consider relevant cases where heaviside pressure source at $z = 0$, zero pressure at $z = l$, and zero initial pressure everywhere.

The partial differential equation (19) is reduced to an ordinary differential equation via Laplace transformation:

$P_{,zz} - \alpha^2 P = 0$ (20)

$$\alpha^2 = s/C_D$$

The general solution is:

$$P = Ae^{-\alpha z} + Be^{+\alpha z} \quad (21)$$

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Applying boundary conditions:

$$\begin{aligned} p(z=0) &= p_0/s = A + B \\ p(z=l) &= 0 = Ae^{-\alpha l} + Be^{\alpha l} \end{aligned}$$

yields

$$5 \quad p(z,s) = \frac{p_0}{s} - \frac{1}{1-e^{-2\alpha l}} (e^{-\alpha z} - e^{\alpha(z-2l)}) \quad (22)$$

The transform is:

$$10 \quad p(z,t) = p_0 \left[1 - \frac{z}{l} - \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \exp \left(\frac{-n^2 \pi^2 C_D t}{l^2} \right) \sin \left(\frac{n\pi z}{l} \right) \right] \quad (23)$$

Pore pressure quickly reduces to dominant exponential behavior with a characteristic time of:

$$15 \quad T_{\text{fluid}} \approx \frac{l^2}{C_D \pi^2} \quad (24)$$

where, from prior discussion $C_D \approx k$. From the above outlined analysis it was found that for the case of no body forces, time independent boundary conditions, and uncoupled flow and deformation, quasi-static flow is governed by a homogeneous diffusion equation in pore pressure alone. Solving for a case involving sudden application of pore pressure, it was discovered that a characteristic time for pressure diffusion and streaming potential depends on flow permeability.

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It has been discovered that by using:

$$C_D = \frac{kK_f}{\mu\phi} \left(1 + \frac{1}{5\phi}\right)^{-1}, \text{ e.g., } K/K_f = 5, K_s = \infty$$

for a variety of natural rocks good agreement is obtained
 5 between measured permeability obtained by using the
 techniques of the present invention and the known
 permeabilities of the samples.

On a time scale long compared to T_{fluid} the streaming
 10 potential exhibits a simple exponential decay characterized by
 the decay time $T_{bellows}$, equation (8), resulting from the
 competition between bellows compression and the drag forces of
 Darcy flow.

15 In one technique for performing the measurement, the
 two streaming potentials V_{13} and V_{23} are digitized and stored.
 T_{fluid} can be derived by using V_{13} as the input waveform,
 V_{23} as the output, and parametrically fitting an impulse
 response of the form:

20

$$h(t) = \exp(-t/T_{fluid}) \quad (25)$$

subject to a minimum least-square error criterion. $T_{bellows}$
 may be found by linear regression. It has been observed that
 25 the estimate of permeability obtained by each of these
 measurements agrees to within 10% of the value obtained by a
 static flow measurement.

In the absense of information regarding matrix
 30 compressional properties it may satisfactory, by an analysis
 of the characteristic response time of the early portions
 T_{fluid} of the respectively induced transient streaming
 potentials to derive a lower bound value for the formation

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permeability. An upper bound value may then be derived from an analysis of later portions belows of the characteristic response time of the induced transient streaming potentials.

It will be understood, of course, that any desired
5 number of outer electrodes can be provided at spaced intervals along the surface of the logging device 27 and the data thereby provided conveniently employed to derive more accurate information of the electrokinetic potentials at different, closer intervals of the formations.

10.

The presence of mud cake on the borehole walls, as is typical of rotary drilled wells, does not have a material effect on the results obtained by the methods of the present invention since the pressure pulses are still effective to 15 compress the formation surface and thereby cause the periodic electrokinetic potentials to be created in the formation. Furthermore, the mudcake may be penetrated for the purpose of direct fluid injection into the formation. Moreover, the mud cakes are typically very much less permeable than earth 20. formation of commercial interest and, therefore, the transient response associated with the movement of the mud filtrate through the cake are very small in comparison to the transient response associated with the formation being investigated. In consequence, the major components of the 25 streaming potential pulses measured are attributable to the movement of the formation fluid through the formation material.

It will be understood by those skilled in the art that
30 the above-described embodiment of the invention is intended to be merely exemplary, and that it is susceptible of modification and variation without departing from the spirit and scope of the invention. For example, other means may be

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employed for applying sonic energy to a formation surface,
such as, for example, an electroacoustical transducer
apparatus of the type disclosed in the prior art U.S. Pat.
No. 3,138,219. All such variations and modifications,
therefore, are included within the scope of the invention as
5 set forth in the appended claims.

I claim:

1. A method for investigating the permeability of earth formations traversed by a borehole characterized by the steps of:
 - 5 positioning a source of periodic mechanical excitation in contact with the surface of the borehole within a formation to be investigated,
 - 10 actuating the source to periodically excite the formation at the area of contact between the formation and the excitation source so as to cause a quasi-static fluid flow condition and accompanying periodic electrokinetic potentials to be produced in the formations;
 - 15 simultaneously with excitation of the formation measuring the magnitude of the electrokinetic potentials excited in the formation; and
 - 20 determining a characteristic response time for the electrokinetic potentials excited in the formation, which response time is related to the permeability of the formation.
- 20 2. Method according to claim 1 further characterized by:
 - sequential exciting the formation at two separate locations,
 - measuring the magnitude of the electrokinetic potentials at said locations, and
 - 25 deriving a differential measurement of the magnitude of the electrokinetic potentials at each of said locations.
- 30 3. Method according to claim 1 or 2 characterized in that the frequencies at which the formation is excited are within the range of up to 1 khz.
4. Method according to any one of claims 1 to 3 characterized in that:

said mechanical excitation source is a mechanical transducer which effects the injection of a fluid into said formation.

5. Apparatus for investigating the permeability of earth formations traversed by a borehole characterized by:
 - a source of periodic mechanical excitation,
 - means for positioning the excitation source in contact with the borehole wall adjacent a formation to be investigated when said apparatus is in a borehole,
10. means for actuating the source so that when the source is adjacent a formation it is effective to periodically excite the formation so as to cause a quasi-static flow condition and accompanying periodic electrokinetic potentials to be produced in the formation; and
15. means within said positioning means for measuring electrokinetic potentials.
6. Apparatus according to claim 5 further characterized by means for determining a characteristic response time of the output of the measuring means.
7. Apparatus according to claim 5 or 6 characterized in that the source of periodic mechanical exitiation comprises a fluid injector.
- 25
8. Apparatus according to any one of claims 5 to 7 characterized in that said actuating means is adapted to effect actuation of the excitation means within a range of frequencies up to 1 khz.
- 30
9. Apparatus according to any one of claims 5 to 8 further characterized by:
 - a body member sized for passage through a borehole;

and characterized in that said positioning means includes a pad device carried on said body member; means carried on said body member for selectively bringing said pad device into engagement with the surrounding borehole surface when said body member is in a borehole; and in that said means for measuring electrokinetic potentials is carried on said pad device.

10. Apparatus according to any one of claims 5 to 9
10 characterized in that said periodic mechanical excitation comprises a fluid injector.

11. Apparatus according to any one of claims 5 to 10
characterized in that said means is adapted to effect
15 actuation of the excitation means within a range of frequencies up to 1 khz.

12. Apparatus according to any one of claims 5 to 11
characterized in that said electrokinetic potentials
20 measuring means comprises a plurality of electrodes arranged in spaced apart relationship about said source.

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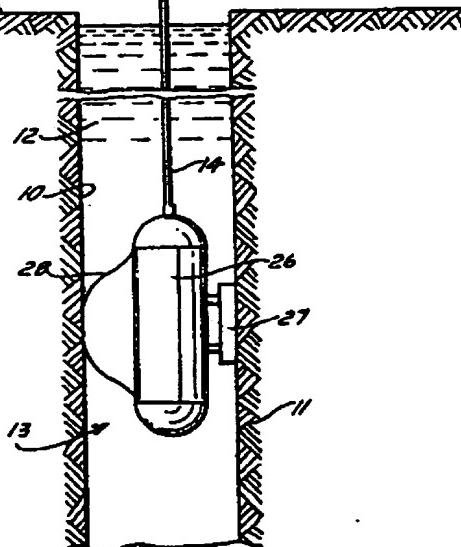
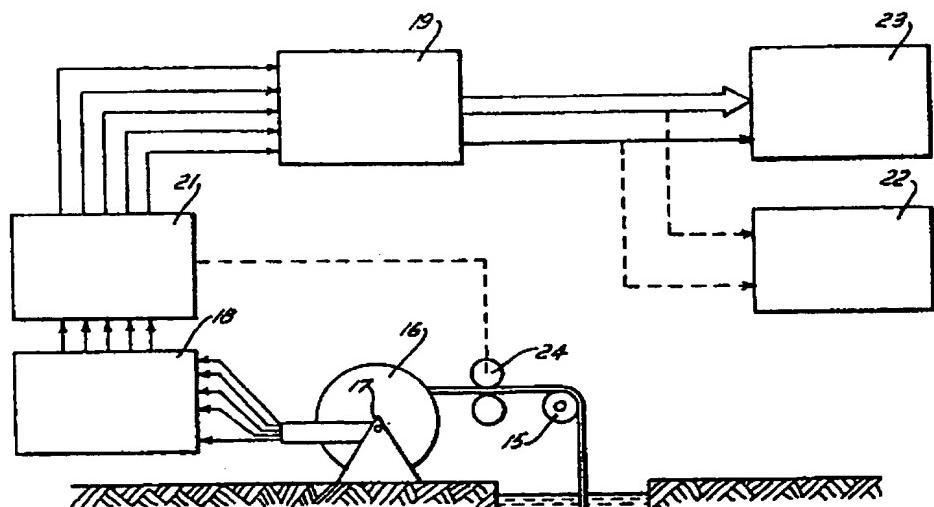


FIG. 1

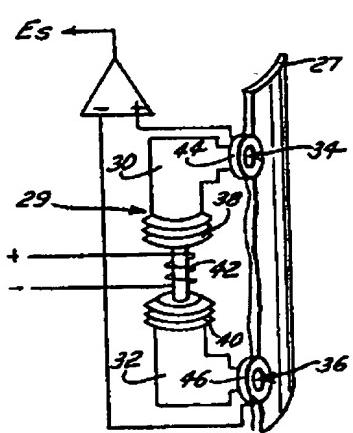


FIG. 2

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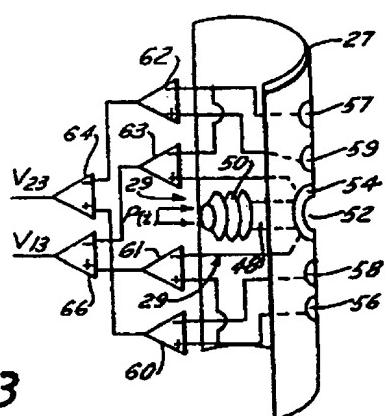


FIG. 3



FIG. 4A

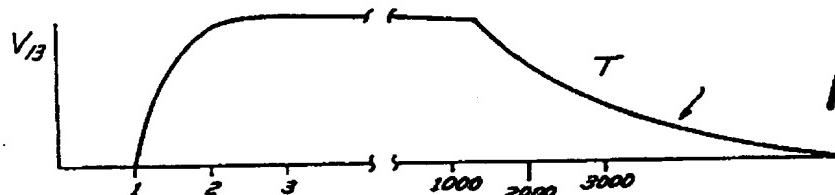


FIG. 4B

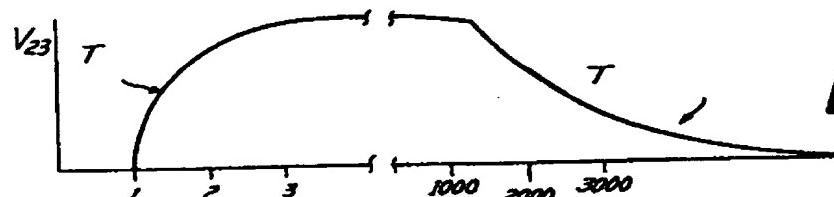


FIG. 4C

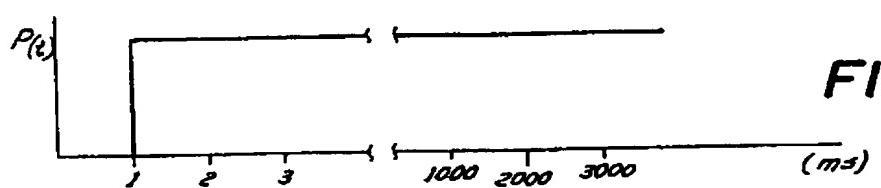


FIG. 4D

EUROPEAN SEARCH REPORT

0043768
Application number

EP 81 40 1063

DOCUMENTS CONSIDERED TO BE RELEVANT			CLASSIFICATION OF THE APPLICATION (Int. Cl.)
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	
	<p><u>US - A - 2 974 273</u> (C.B. VOGEL & D. WEISER)</p> <p>* column 2, lines 13-37 *</p> <p>--</p> <p><u>US - A - 2 475 354</u> (H.G. DOLL)</p> <p>* column 1, line 44 to column 3, line 9; column 3, line 66 to column 4, line 42; figure 1 *</p> <p>--</p> <p><u>US - A - 2 433 746</u> (H.G. DOLL)</p> <p>* column 2, line 5 to column 3, line 75 *</p> <p>--</p> <p><u>US - A - 4 043 192</u> (L.Z. SHUCK)</p> <p>* column 2, lines 5-17 and line 50 to column 3, line 8 *</p> <p>--</p> <p>D <u>US - A - 3 599 085</u> (A. SEMMELINK)</p> <p>* column 4 to column 5, line 45; figure 1 *</p> <p>--</p> <p>D <u>US - A - 2 814 017</u> (H.G. DOLL)</p> <p>* column 1, line 51 to column 2, line 29 *</p> <p>-----</p>	1,5	G 01 V 3/26
			TECHNICAL FIELDS SEARCHED (Int. Cl.)
			G 01 V 3/26 3/08 3/18 11/00 E 21 B 49/10 47/10
			CATEGORY OF CITED DOCUMENTS
			X: particularly relevant A: technological background O: non-written disclosure P: Intermediate document T: theory or principle underlying the invention E: conflicting application D: document cited in the application L: citation for other reasons
			&: member of the same patent family. corresponding document
 <p>The present search report has been drawn up for all claims</p>			
Place of search	Date of completion of the search	Examiner	
The Hague	5-10-1981	KUSCHBERT	